Shallow Shear Wave Reflection Survey in the Canadian Arctic

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SUMMARY

Shear wave seismic reflection was used to delineate cyclic deposits of massive ice and glacial till in the upper 30 m at a site near Tuktoyaktuk, Northwest Territories, Canada. Shear wave reflections with dominant frequencies in excess of 350 Hz were recorded with a steel shaft and 1 kg hammer source and single 50 Hz horizontal geophones with 30 cm spikes. A least four reflecting interfaces between 10 and 30 m depth can be correlated to borehole data. Previous regional borehole information suggested the presence of a single massive layer of segregated ice beneath glacial till. The seismic data were interpreted to indicate at least three distinct layers of structurally deformed ice that were later confirmed by drilling and geophysical logs.

INTRODUCTION

Permafrost environments present a unique challenge to the construction of permanent installations. Future development of both on-shore and off-shore petroleum reserves near the northern part of the Mackenzie River Valley, as well as in the Beaufort Sea, will require major investment in structures related to transportation as well as extraction. A permafrost environment with massive near-surface ice layers represents one of the most difficult scenarios for the construction of substantial surface structures. Any thermal disturbance can result in melting and has the potential for economic and environmental disaster. Development of geophysical methods to detect and map shallow ice layers over large areas has been an active research area of the Geological Survey of Canada for many years.

Shallow shear wave reflection techniques have been effectively used in mapping bedrock and intra-alluvial layers, detecting fissures, fractures, and faults, determining Poisson's ratio in situ (Hasbrouck, 1991; Pullan et al., 1990; Miller et al., in press). Shear wave reflection methods can potentially resolve thinner layers at shallower depths than compressional wave methods at similar frequencies because of the lower shear wave velocities. The polarized nature of shear waves allows for improved data quality through energy focusing and compressional wave noise suppression. Shear waves in general should produce better results than compressional waves in areas where the surface materials are dry, coarse-grained, and unsorted, due to the insensitivity of shear waves to moisture content. In areas where high frequency broad band shear waves can be produced, propagated, and recorded, shear wave reflection surveys thus offer several advantages over more traditional compressional wave surveys.

The Geological Survey of Canada has actively studied the permafrost regions of the Arctic (both Canadian and Russian) for many years. This shear wave study targeted a till/ segregated ice interface inferred from seismic shot hole data to be at approximately 30 m deep in an area just south of Tuktoyaktuk, Northwest Territories (Figure 1). Core drilling, geophysical logging, and borehole seismic studies were undertaken to complement and confirm interpretations of the reflection data. Because of the extreme lateral variability in the subsurface stratigraphy in this area, shallow reflection methods could be more effective and more useful than drilling.

GEOLOGY

The age of the near-surface material in this area of the Mackenzie River Valley is imperfectly known based on radio-carbon dating but is at least Pleistocene (Rampton, 1988). The surface material is glacial till with a high concentration of clay. Strong evidence indicates reworking of these tills by the Mackenzie River. Massive ice units, identified as segregated ice, were formed in place at the base of the clay till layer by the downward growth of the permafrost. The growth of these massive ice layers proceeds as water is transported upward to the freezing front through sands and gravels beneath the clay till layer. The near-surface non-permeable clay till acts as a natural boundary restricting upward propagation of this ice layer. Late Wisconsin glaciation over-rode and structurally deformed these lenticular till and ice formations leaving a structurally complex setting. Locally, late Wisconsin glaciation has pushed ice layers as much as 40 to 50 km. The stratigraphy of the upper several hundred meters at this site could be structurally altered with overturned beds and relatively high-angle dip as a result of glaciation.

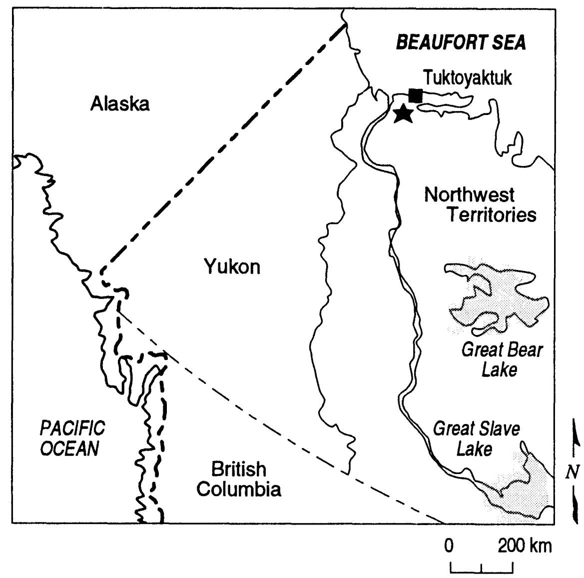

Figure 1. Site map indicating the location of seismic survey .

DATA ACQUISITION AND PROCESSING

The reflection data were acquired in the "spring" (March) of 1993 using an EG&G Geometrics 2401 seismograph configured for 12 channels and a 1/20 msec sampling interval. The 50 Hz horizontal geophones, on 0.3 m spikes, were planted in the frozen ground with the aid of an electric drill at the base of 0.3 to 0.6 m deep holes dug through the snow cap. The drill effectively melted the frozen ground and once the geophone was placed in the drill hole the spike froze in place. The source was a 1 m x 0.02 m steel shaft driven into the frozen ground (seated) at a 45 degree angle perpendicular to the survey line and then impacted with eight blows from a 1 kg hammer. The eight shot stacks were summed and stored as a single record. Geophones were separated by 1 m and shots were recorded every 1/2 m.

Two different offsets were used to increase the apparent spread length while maintaining a 1 m station spacing. This combination of recording equipment and acquisition method maximized the data quality and quantity while minimizing the effort of recording data in this very harsh environment.

The reflection data were processed into a CDP stacked section with a maximum apparent fold of 12. The processing flow was very similar to that used for petroleum data. The major distinction relates to the emphasis placed on the non-computation portion of the pre-stack phase. A significant amount of effort was directed at editing, filtering, and scaling. Ice wedges act as scatter sources for seismic energy. To reduce the amount of scatter present on the CDP stacked section a negative slope removal f-k filter was applied to reduce the amplitude of energy with a negative linear slope. The f-k filter did not “uncover” any reflection arrival not previously interpretable. The filter did improve the signal-to-noise ratio, allowing a more confident overall interpretation.

The borehole drilled at station 5 10 produced approximately 30 m of continuous core, a suite of geophysical logs, and a three-component uphole survey (Figure 2). The placement of the borehole was based on a preliminary CDP stacked section produced during the acquisition portion of the project. Three boreholes were drilled with only BH-93-2 having a depth greater than 12 m. The gamma ray log clearly indicates the lithologic changes from ice to clay till at several places in the borehole. The borehole seismic data were reduced to a time-depth curve to allow accurate velocity determinations and one-way travel times for particular subsurface interfaces. Borehole seismic data provided continuity between the CDP stacked section, the geophysical logs, and core. The correlation among the borehole and surface seismic data and the logs strengthens interpretations based on CDP stacked data.

RESULTS

Identification of reflected energy on field files is essential. No confidence can be placed in CDP stacked data unless a solid tie between individual shot gathers and the CDP stacked data can be established. Four shot gathers selected from across the expanse of the survey line strongly support the presence of interpretable reflections on CDP stacked data (Figure 3). Digital filtering enhances several reflections previously suspected on raw data. An f-k filter designed to remove all coherent events with a negative slope between 1200 and 1700 m/sec was applied to attenuate scatter suspected to be from ice wedges. The f-k filter further enhanced the reflection events interpreted on both the raw field data and the digitally filtered data. After careful examination, no coherent event interpretable as a reflection could be found on the final f-k filtered data that is not present on the raw data.

At least four unique reflection events can be interpreted at station location 510 (Figure 4). The information obtained from borehole BH-93-2 is consistent with the interpretation of reflections on the stacked section (Figure 2). The 3-component uphole survey revealed three distinct velocity layers. Correlation of the borehole seismic data with the gamma ray log suggests the interface on the CDP stack interpreted at about 15 msec is most likely the base of the clay till and top of the first thick ice layer at approximately 10 m deep. The second strong reflection event interpreted at about 25 msec is interpreted to be the base of this massive ice unit and the top of the second clay till layer at a depth of approximately 17 m. The third reflection event interpreted southwest of station 490 is probably the top of the deepest massive ice encountered in the borehole at about 20 m. A fourth reflection is interpreted at about 41 msec; however, the exact lithologic origin of this event cannot be confidently

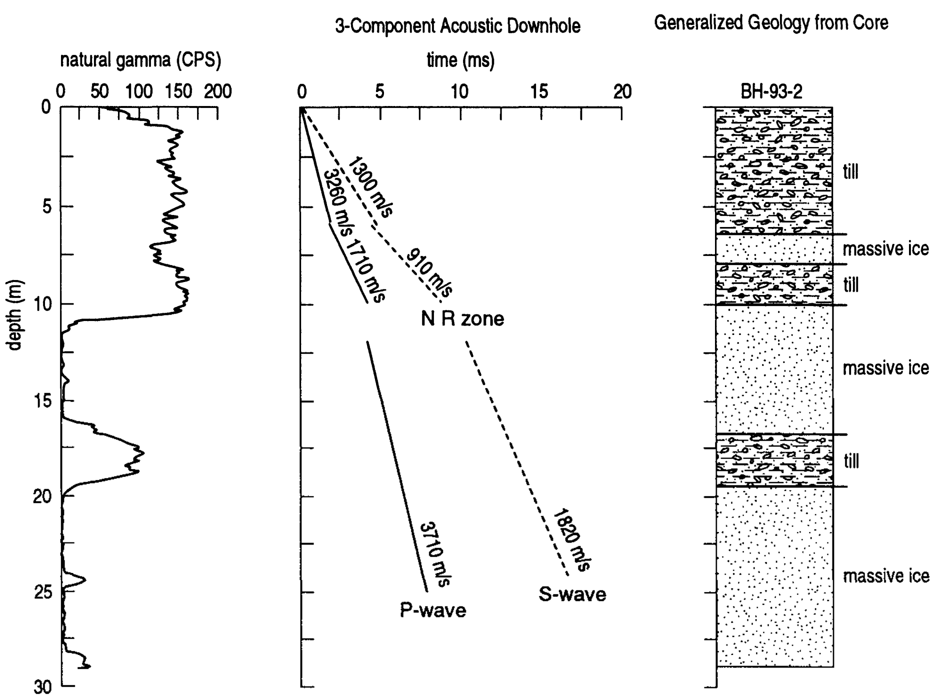

Figure 2. Logs and associated analysis from BH-93-2 located at approximate station 510.

determined as the borehole was only 30 m in depth. The reflection events have a dominant frequency in excess of 350 Hz, and with an average velocity on the order of 1600 m/sec the vertical resolution potential of this survey should be approximately 1 m.

The general interpretation of the CDP stacked section is consistent with the suggestion that the area is structurally altered by glaciation. The ice/till layers form lenses that seem to pinch out or thin to a thickness less than resolvable by this survey. The massive ice interpreted in BH-93-2 at 11 m depth appears to thin to the northeast with an associated thickening of the thin till layer interpreted at 17 m of depth. It could be inferred that the till/ice interface at approximately 10 to 11 m depth is consistent across the expanse of this line with only a subtle indication of a localized northeastward dip. Alternately, the disturbance between 15 and 30 msec at station 490 could be associated with stratigraphic changes in the materials in the same interval on the far southwestern portion of the line (around station 400). The significant amount of geologic information that can be inferred from this short stacked section suggests that more laterally extensive surveys could effectively detect and delineate massive shallow ice formations.

CONCLUSIONS

Shallow shear wave reflection techniques in association with geophysical and geological logs are an effective method of detecting and mapping massive ice formations at depths less than 30 m at this site south of Tuktoyaktuk, Northwest Territories, Canada. With continued development this method could be effectively used as a reconnaissance tool for surface and shallow subsurface structures in permafrost areas.

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REFERENCES

Hasbrouck, W.P., 1991, Four shallow-depth, shear-wave feasibility studies: Geophysics, 56, 1875-1885.

Miller, R.D., D.W. Steeples, K.W. King, and R.W. Knapp, 1993, In situ Poisson's ratio measurements near Provo, Utah; in The Assessment of Regional Earthquake Hazards and Risk along the Wasatch Front, Utah, USGS professional paper #1500K-Z, Paula L. Gori and Walter W. Hays, eds: U.S. Geological Survey, Reston, Virginia, in press.

Pullan, S.E., Hunter, J.A., and Neave, K.G., 1990, Shallow shear-wave reflection tests: Exp. Abstrs. of Technical Program with Biographies, SEG, 60th Annual Meeting, San Francisco, California, 380-382.

Rampton, V.N., 1988, Quaternary geology of the Tuktoyaktuk coastlands, Northwest Territories: Geological Survey of Canada, Memoir 423, 98 pp.

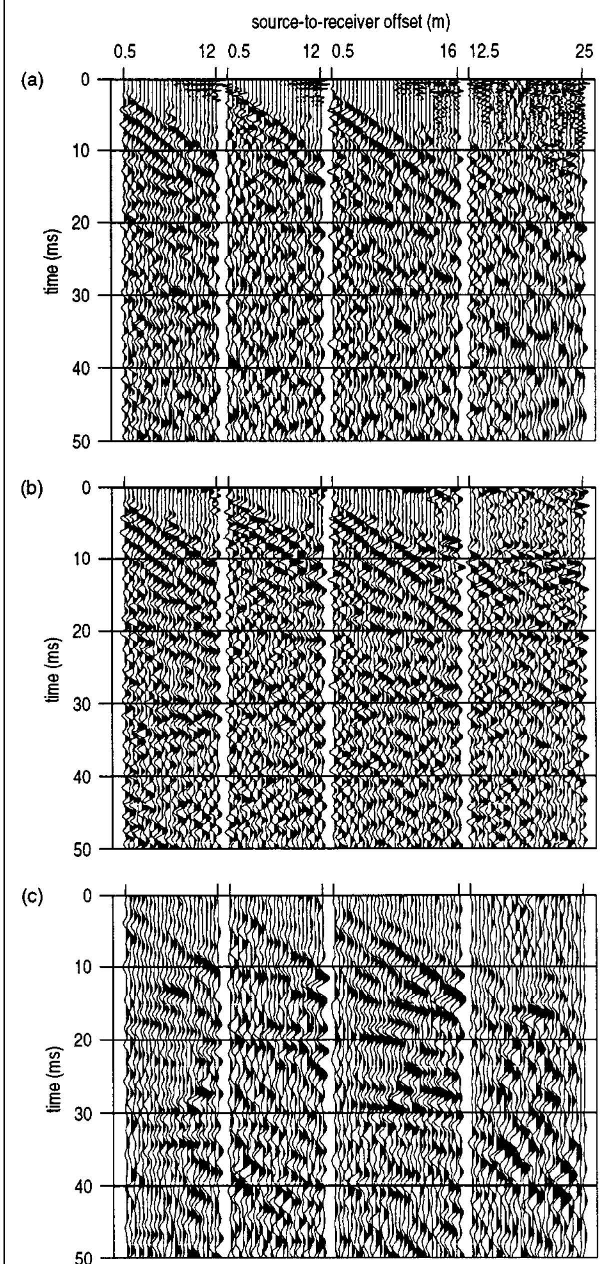

Figure 3.Selected shot gathers from across the line, a)raw data, b) digital filtered data, and c) reverse f-k filter.

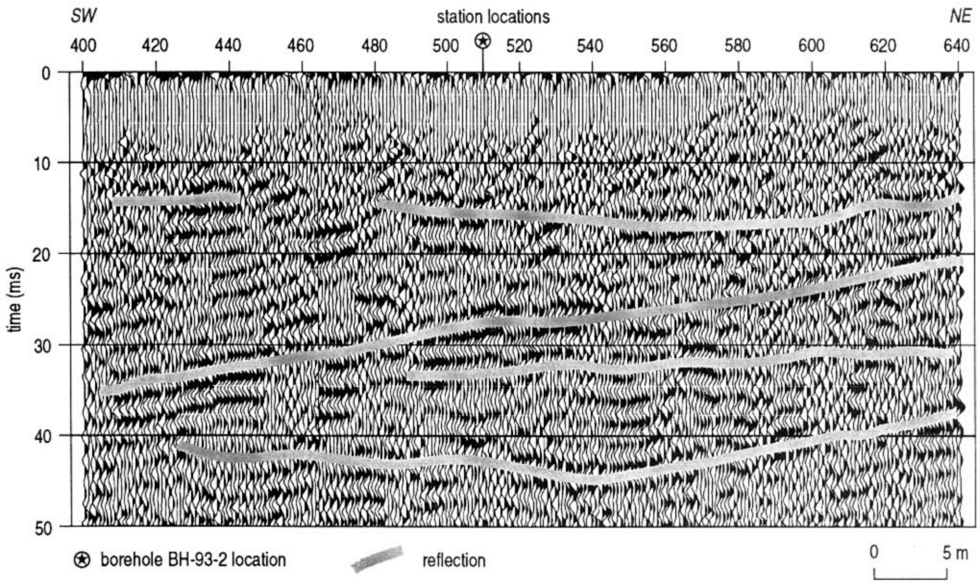

Figure 4. Interpreted CDP stacked section.